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The Top Ten solar analogs in the ELODIE library *

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Abstract. Several solar analogs have been identified in the library of high resolution stellar spectra taken with the echelle spectrograph ELODIE. A purely differential method has been used, based on the χ^2 comparison of a large number of G dwarf spectra to 8 spectra of the Sun, taken on the Moon and Ceres. HD 146233 keeps its status of closest ever solar twin (Porto de Mello & da Silva, 1997). Some other spectroscopic analogs have never been studied before, while the two planet-host stars HD095128 and HD186427 are also part of the selection. The fundamental parameters found in the literature for these stars show a surprising dispersion, partly due to the uncertainties which affect them. We discuss the advantages and drawbacks of photometric and spectroscopic methods to search for solar analogs and conclude that they have to be used jointly to find real solar twins.

Key words. Stars: fundamental parameters – Sun

1. Introduction

The Sun is the best-known star : its fundamental parameters (radius, mass, age, luminosity, effective temperature, chemical composition) are known with a good accuracy, as well as its internal structure, activity, velocity field and magnetic field. Consequently the Sun is used as the fundamental standard in many astronomical calibrations. One of the motivations to identify stars that replicate the solar astrophysical properties is the necessity to have other reference stars, observable during the night under the same conditions as any other target. The pioneers of the subject (Hardorp 1978, Cayrel de Strobel et al 1981) were also involved in resolving the problem of the photometric indexes of the Sun, inherent to the impossibility to observe it as a point-like source. In the last decade the motivation of finding such stars has been increased by an exciting challenge : the search for planetary systems that could harbour life. Solar analogs are straightforward targets for this hunt.

The first searches of solar analogs were performed by photometric and spectrophotometric techniques. Hardorp (1978) compared UV spectral energy distributions of nearly 80 G dwarfs to that of the Sun and found 4 stars that had a UV spectrum indistinguishable from solar : HD028099 (Hy VB 64), HD044594, HD186427 (16 Cyg B), HD191854. Neckel (1986) established a list of bright stars with UBV-colours close to those of the Sun and confirmed the photometric resemblance of Hy VB 64 and 16 Cyg B to the Sun. With the advance of techniques in high resolution spectroscopy and solid state detectors, and with the progress in modelling stellar atmospheres, measurements of ($T_{\rm eff}$, $\log g$, [Fe/H]) became of higher precision allowing the search for solar analogs by comparing their atmospheric parameters to those of the Sun. G. Cayrel de Strobel made a huge contribution to the subject with the detailed analysis of many candidates (Cayrel de Strobel et al 1981, Cayrel de Strobel & Bentolila 1989, Friel et al 1993) and a review of the status of the art (Cayrel de Strobel 1996). She also introduced the concepts of solar twin, solar analog and solar-like star. Porto de Mello & da Silva (1997) presented the star HD146233 (18 Sco) with physical properties extremely close to those of the Sun, as the "closest ever solar twin".

A workshop on Solar Analogs was held in 1997 at the Lowell Observatory to provide a solid basis to the hunt of solar analogs. After many discussions on the performances of different methods, a list of the best candidates was established, in which 4 stars received the agreement of almost all participants : HD217014 (51 Peg), HD146233 (18 Sco), HD186408 (16 Cyg A), HD186427 (16 Cyg B).

In this paper, we take advantage of a large and homogeneous dataset of high resolution echelle spectra which are compared directly to solar spectra, independently of any model or photometric measurements. The eye is replaced by a more reliable criterion, approximatively the reduced χ^2, computed over ~ 32000 resolution elements. This purely differential method allowed us to identify sev-

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eral stars whose optical spectrum looks closely like the Sun's, the best one being HD146233.

We describe in Sect. 2 our observational material and differential method, and we give the list of our Top Ten solar analogs. We have searched the literature for their colour indexes and atmospheric parameters and calculated absolute magnitudes from Hipparcos parallaxes. We discuss the uncertainties which affect these data and compare them to that of the Sun (Sect. 3). In Sect. 4, we examine qualitatively their Li content and give information on their activity and age. In Sect. 5 we discuss several stars, having similar colours and absolute magnitude or similar atmospheric parameters as the Sun but slightly different spectra.

2. ELODIE spectra and the TGMET code

All the spectra used in this paper were extracted from the library of stellar spectra collected with the echelle spectrograph ELODIE at the Observatoire de Haute-Provence by Soubiran et al (1998) and Prugniel & Soubiran (2001). The performances of the instrument mounted on the 193 cm telescope, are described in Baranne et al (1996). ELODIE is a very stable instrument, built to monitor radial velocity oscillations of stars with exoplanets, at a resolving power of 42 000 in the wavelength range 3850–6800 Å. The stability of the system makes it possible to compare spectra taken at different epochs. Spectrum extraction, wavelength calibration and radial velocity measurement by cross-correlation have been performed at the telescope with the on-line data reduction software.

The current version of the Elodie library includes 1962 spectra available in the Hypercat database[1], most of the spectra having a signal to noise ration (S/N) at 550 nm greater than 100. We have selected 208 spectra of G dwarfs with the following criteria : $0.55 < B-V < 0.75$ ($(B-V)_{\odot} \simeq 0.65$) and $4 < M_{\rm V} < 5.6$ ($M_{{\rm V}\odot} \simeq 4.82$). Absolute magnitudes have been computed from Hipparcos parallaxes, the selected stars having relative errors smaller than 10%. The list includes 8 spectra of the Sun (Table 1).

Table 1. List of the solar spectra used in this study.

Hypercat number	date of observation	object	FWHM $km.s^{-1}$	S/N at 550 nm
00903	14/01/1998	Moon	11.061	381.4
00904	22/12/1999	Moon	11.050	268.5
00905	22/12/1999	Moon	11.050	139.6
00906	22/12/1999	Moon	11.061	156.5
00907	27/03/2000	Ceres	11.017	117.5
00908	24/01/2000	Moon	11.057	200.0
00909	24/01/2000	Moon	11.054	224.9
01964	22/08/2000	Moon	12.126	404.3

[1] www-obs.univ-lyon1.fr/hypercat/11/spectrophotometry.html

The stellar spectra were compared to solar ones with the TGMET code developed by Katz et al (1998). TGMET is a minimum distance method which measures similarities between spectra in a quantitative way. The TGMET comparison between 2 spectra includes the following steps :

– straightening of each order
– removal of bad pixels, cosmic hits and telluric lines
– wavelength adjustment
– mean flux adjustment by weighted least squares, order by order

The wavelength adjustment shifts the comparison spectrum to the radial velocity of the solar spectrum and resamples it to the same wavelenghts. It implies an interpolation between wavelengths which is performed with the quadratic Bessel formula. The flux fitting of the comparison spectrum to the solar spectrum assumes that the 2 spectra differ by a simple factor (the 2 stars having roughly the same temperature it is not necessary to introduce a slope). Once the two spectra have been put on a common scale, a distance between them can then be computed. As explained in Katz et al (1998), instead of adopting the real reduced χ^2 of the fit as the distance between 2 spectra, which would imply taking into account the noise on each pixel, the response curve was chosen as the weighting function. This distance was adopted after many tests and was proven to produce the most satisfactory results, especially at high S/N. Its advantage is that it gives a similar weight to the continuum and to the wings and bottom of absorption lines, contrary to a weighting function based on the photon noise.

Katz et al's algorithm includes a convolution step which is not included in the present work. A convolution should be performed in order to put the 2 compared spectra at exactly the same resolution. A difference in resolution between two spectra is the result either of a variation of the instrumental resolution between the two exposures or of intrinsic physical properties of the observed stars like rotation, macroturbulence or binarity which enlarge their spectral profile. But as we are looking for solar twins, these intrinsic properties are important in the criterion of similarity and should not be erased. Moreover ELODIE is a very stable instrument and its resolution does not vary significantly with time. It can be seen in Table 1 that all of our solar spectra have a resolution of 11 $km.s^{-1}$ (FWHM), except the spectrum 01964 which is sligthly degraded (12 $km.s^{-1}$). These considerations led us to supress the convolution step in the TGMET algorithm.

In practice we have limited the comparison to the wavelength range 4400–6800 Å (orders 21 to 67) and eliminated the under-illuminated edges of the orders. Finally distances between spectra have been computed over nearly 32000 wavelengths. Table 2 gives an example of the TGMET output, for solar spectra 00903 (S/N=381.4) and 00907 (S/N=117.5). The output in the two cases is consistent, with however some differences : HD088072 is within

the 20 closest neigbours of 00903 but not of 00907, the opposite is the case for HD071148 and HD042618. These differences, probably related to observing conditions, are smoothed when combining the TGMET results obtained for the 8 solar spectra, the combination being performed by averaging the distances, order by order, giving a different weight to several orders (see below). The score obtained by each solar analog was our criterion of closeness to the Sun, leading the final Top Ten list : HD146233, HD168009, HD010307, HD089269, HD047309, HD095128, HD042618, HD071148, HD186427, HD010145.

Fig. 1 shows the fit of HD146233 to spectrum 00903, for order 39 including the MgI triplet and order 64 including the H_α line. For order 39, the fit has been performed on 773 points; the mean difference between the solar flux and the fitted fluxes of HD146233 is 3 electrons with a standard deviation of 1157 electrons, corresponding to 1% of the mean flux (108772 electrons). For order 64, the difference is also 1% (743 points, mean difference of - 57 electrons, standard deviation of 2166 electrons, mean flux of 210319 electrons).

Fig. 2 shows for the Top Ten solar analogs their distance to the solar spectrum 00903, order by order. It is very clear from Fig. 2 that HD146233 is very similar to the Sun and that HD168009 is not very far behind. The closeness of these 2 stars is confirmed for the 7 other solar spectra. The largest discrepancies occur for order 63 (648 - 652.5 nm). The examination of this order indicates that it is polluted by telluric lines which were not completely removed. Telluric lines unfortunatly affect also order 64 which is our best indicator of temperature thanks to the H_α line. The dispersion obtained on order 64 is much higher than that on order 31 which includes the H_β line. However, the H_β line being at the edge of the order it has a lower weight in the fit because of under-illumination. A large dispersion on order 39, which includes strong features due to the MgI triplet, is also seen for each solar spectrum. This region is known to be very sensitive to the 3 atmospheric parameters ($T_{\rm eff}$, $\log g$, [Fe/H]) and consequently powerful for discriminating solar twins. These considerations led us to adopt a higher weight of 3 on order 39, a half weight on order 64 and a null weight on order 63 when combining the information on all the orders.

3. Atmospheric parameters and photometry

We report in this section colour indexes available in the literature for our Top Ten solar analogs and visual absolute magnitudes deduced from their Hipparcos parallaxes (Table 4). We also review recent determinations of their atmospheric parameters. These data are compared to those of the Sun, and uncertainties which affect them are discussed. Finally we report their occurrence in previous studies of solar analogs.

The $B-V$ and $U-B$ colours come from the General Catalogue of Photometric Data (Mermilliod et al 1997), except for HD047309 for which we have taken the $B-V$ colour from Tycho2 (Høg et al 2000) transformed to the Johnson system. The b-y colours are extracted from the catalogue by Hauck & Mermilliod (1998).

The photometry of the Sun is a matter of debate. Neckel (1986) has determined $(B-V)_\odot = 0.650 \pm 0.005, (U-B)_\odot = 0.195 \pm 0.005, M_{\rm V\odot} = 4.82 \pm 0.025$, values which are adopted as basic solar data in Allen's Astrophysical Quantities (2000). Cayrel de Strobel (1996) gives a compilation of solar $(B-V)$ colours measured by different techniques and determines from the relations colour vs Teff : $(B-V)_\odot = 0.642 \pm 0.004, (b-y)_\odot = 0.404 \pm 0.005$. Porto de Mello & da Silva (1997) obtain with a similar method : $(B-V)_\odot = 0.648 \pm 0.006, (U-B)_\odot = 0.178 \pm 0.013$. We list in Table 4 a reasonable range of values for the Sun's colours and absolute magnitudes.

3.1. HD146233

HD146233 (18 Sco) was adopted at the Solar Analogs workshop at Lowell Observatory as one of the best solar twins. Our study confirms with independent data and methods the result of Porto de Mello & da Silva (1997) quoting HD146233 as THE closest ever solar twin. In the optical range, its spectrum is indistinguishable from that of the Sun (Fig. 1). Before that, Hardorp (1978) using UV spectrophotometry mentioned this star as a solar analog but with the comment "spectrum similar to solar, some absorption features weaker". However, this study was based on a single low-resolution spectrum. This discrepancy is discussed by Porto de Mello & da Silva (1997) and by Cayrel de Strobel (1996).

Only 2 determinations of atmospheric parameters are available for this star, in very good agreement, giving solar values within the error bars. HD146233 seems to be more luminous than the Sun by 0.05 mag. Its parallax is very accurate ($\pi = 71.30 \pm 0.89$ mas), but one may legitimely wonder if its photometry is sufficiently accurate to consider this excess of luminosity real. As a matter of fact HD146233 is part of the Catalogue of suspected variables by Kukarkin et al (1981) who found a possible amplitude of 0.11 mag. V magnitudes, measured by several authors between 1957 and 1978 and available in the GCPD (Mermilliod et al 1997), range effectively between V=5.48 and V=5.56. The average $V = 5.504 \pm 0.015$ was used to compute an absolute magnitude of $M_{\rm V} = 4.77$. Thus if HD146233 is slightly variable, a higher luminosity than the Sun cannot be clearly established. But more recently HD146233 was identified by Adelman (2001) to be part of the 681 most photometrically stable stars during the 5 years of the Hipparcos mission, with an amplitude of 0.01 mag. Its median magnitude in the Hipparcos system is $H_p = 5.6265 \pm 0.0005$. According to the photometric transformation calibrated by Harmanec (1998), the corresponding apparent visual magnitude is $V = 5.493 \pm 0.003$ which confirms its higher luminosity.

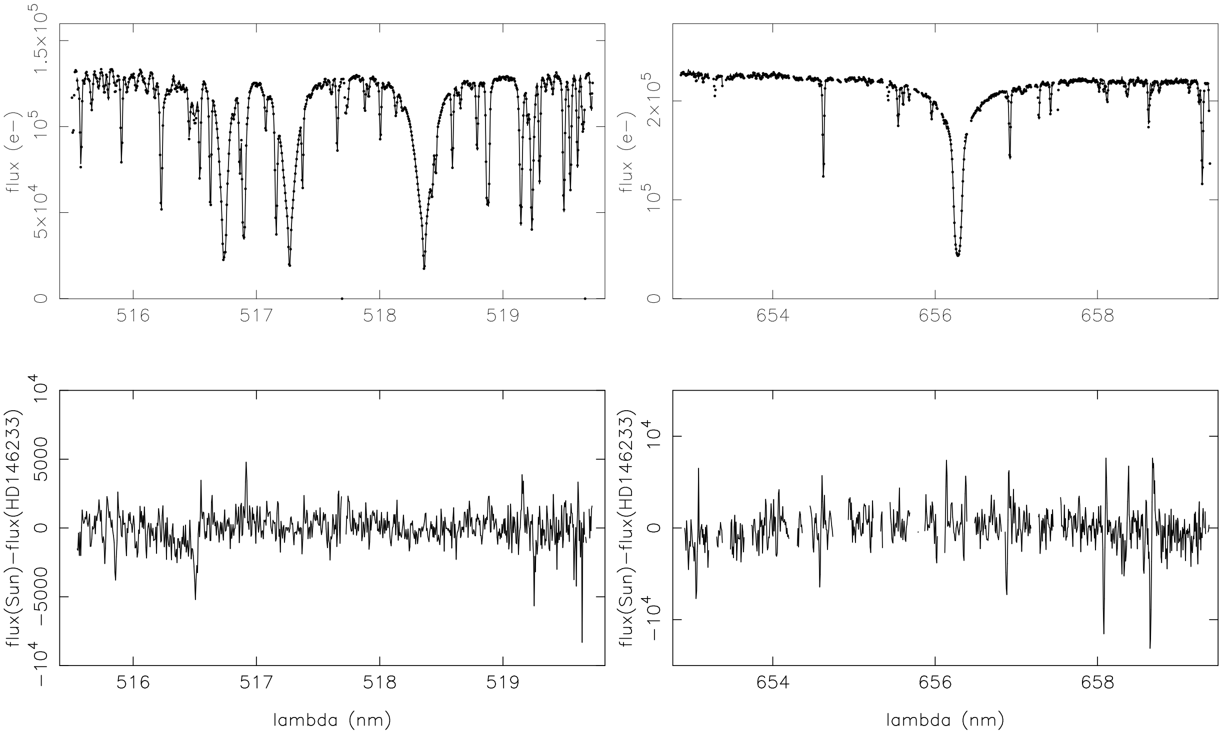

Fig. 1. Comparison of one of the solar spectra (dots) with HD146233 (continuous line) in the spectral region of the MgI triplet and H_α line.

Table 2. The 20 closest spectra of the solar spectra 00903 and 00907, deduced by the TGMET code.

n°	star	S/N	distance	n°	star	S/N	distance
	00903				00907		
01964	Sun	404.3	2.220	00903	Sun	381.4	1.158
00909	Sun	224.9	2.332	00909	Sun	224.9	1.175
00908	Sun	200.0	2.410	01964	Sun	404.3	1.183
00490	HD146233	236.8	2.789	00908	Sun	200.0	1.188
00906	Sun	156.5	2.910	00490	HD146233	236.8	1.243
00905	Sun	139.6	3.110	00906	Sun	156.5	1.250
01633	HD168009	204.9	3.305	00905	Sun	139.6	1.275
00904	Sun	268.5	3.392	01633	HD168009	204.9	1.329
00907	Sun	117.5	3.474	00904	Sun	268.5	1.382
01187	HD047309	119.7	3.841	00039	HD010307	198.4	1.457
01188	HD047309	108.8	3.864	01634	HD168009	134.6	1.458
01634	HD168009	134.6	3.875	01187	HD047309	119.7	1.471
00039	HD010307	198.4	3.937	00346	HD071148	117.0	1.472
00895	HD089269	225.9	3.978	00895	HD089269	225.9	1.478
00258	HD047309	100.9	4.176	01188	HD047309	108.8	1.493
00387	HD088072	86.5	4.236	00400	HD095128	181.9	1.555
00699	HD186427	139.9	4.283	00258	HD047309	100.9	1.557
00400	HD095128	181.9	4.336	00981	HD010307	162.9	1.560
00981	HD010307	162.9	4.342	01125	HD042618	132.5	1.591
00038	HD010145	153.2	4.346	00699	HD186427	139.9	1.594

3.2. HD168009

HD168009 has been quite well studied but has never been mentioned as a good solar analog, despite its being part of the list of "bright stars with UBV-colours close to those of the Sun" established by Neckel (1986). According to its spectroscopic gravity and absolute magnitude, HD168009 is more luminous than the Sun. Its absolute magnitude $M_V = 4.52$ is quite reliable and relies on a parallax of $\pi = 44.08 \pm 0.51$ mas. Several estimations of its apparent visual magnitude are in good agreement : V=6.295 according to the GCPD, V=6.309 according to Simbad,

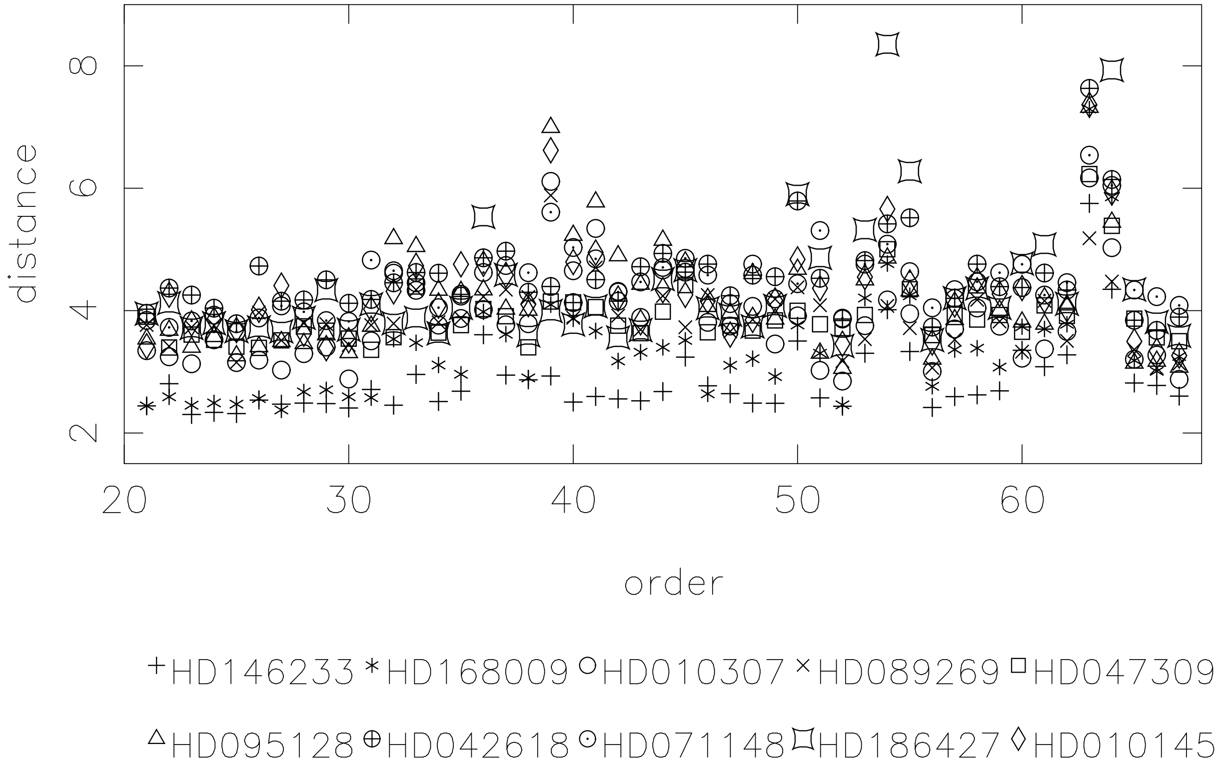

Fig. 2. Distance of the Top Ten solar analogs to solar spectrum 00903, order by order.

V=6.307 according to Tycho2. Its $B-V$ colour index is slightly more uncertain : $B-V=0.635$ according to the GCPD, $B-V=0.604$ according to Simbad, $B-V=0.646$ according to Tycho2, but suggests however a higher temperature than the Sun. This is confirmed by several recent estimates of Teff available in the literature and spanning values from 5719K (Chen et al 2000) to 5833K (Blackwell & Lynas-Gray 1998) with a mean value of 5801K. This large dispersion is a good illustration of the lack of a common temperature scale, even for bright nearby stars. HD168009 is also part of a catalogue of high precision near infrared photometry by Kidger & Martin-Luis (2003) who give J=5.133, H=4.840, K=4.783, values which differ by less than 0.005 mag from those measured by Alonso et al (1998). A colour index V-K=1.512 leads to Teff=5730 K with the relation established by Alonso et al (1996b).

The abundance of several elements (O, Na, Mg, Al, Si, K, Ca, Ti, V, Cr, Ni, Ba) have been measured by Chen et al (2000) to be solar within the error bars. Ba, Eu and Sr abundances have also been measured by Mashonkina & Gehren (2001), leading to the same conclusion.

3.3. HD010307

Like HD168009, HD010307 seems to be hotter and more luminous than the Sun. Allende Prieto et al (1999) quote a mass of $0.94M_{\odot}$ and an astrometric gravity of logg=4.29, in very good agreement with the averaged spectroscopic gravity of logg=4.26 quoted in Table 4. HD010307 is in fact a binary system which was resolved by Henry et al (1992), the low mass companion being 1000 times fainter. According to a detailed analysis of Hipparcos data by Martin et al (1998) the system has a total mass of $(0.931 \pm 0.178)M_{\odot}$, a primary mass of $(0.795 \pm 0.159)M_{\odot}$ and a secondary mass of $(0.136 \pm 0.053)M_{\odot}$. At a distance of 12.6 pc (12.4 pc when the binarity is considered), it is the nearest of our Top Ten solar analogs. It is a well studied star with many measurements in good agreement of its apparent visual magnitude and $B-V$ colour, and it is part of the catalogue of the least variable stars compiled by Adelman (2001) despite its binarity. We notice that the temperature given by Chen et al is similar to that of the Sun but significantly lower than given by other authors, as was also the case for HD168009. Hardorp (1978) mentioned HD010307 with the comment "some aborption features appreciably weaker than solar" which is in agreement with a higher temperature.

Cayrel de Strobel (1996) and Fesenko (1994) have included HD010307 in their list of solar analogs but not with a high rank. It was only mentioned to "deserve study" in the conclusions of the Lowell Workshop.

3.4. HD089269

Very few papers mentioning HD089269 are available in the literature. It was never recorded as a solar analog despite its colour index $B-V=0.654$ being similar to that of the Sun. Its visual magnitude V=6.633 combined to its trigonometric parallax $\pi = 48.45 \pm 0.85$ mas leads to an absolute magnitude $M_{\mathrm{V}} = 5.06$ indicating that it is

less massive than the Sun. Mishenina et al (2003) find it 100K colder than the Sun and significantly more metal poor. The good score obtained with TGMET indicates that, globally, the combined effects of temperature and iron abundance may give similar absorption features as in the Sun.

3.5. HD047309

HD047309 is unknown as a solar analog. The only data are Strömgren photometry, and data from Hipparcos and Tycho2. Contrary to HD089269, it seems to be slightly hotter, more luminous and metal-rich. It is also the most distant of our sample at 42.4 pc.

3.6. HD095128

We come back to well a known star with HD095128 (47 UMa) known to have two giant planets orbiting around it. Consequently it has been very well studied. Its temperature is significantly higher than that of the Sun. Again the temperature given by Chen et al is the lowest of the list with 5731K whereas Santos et al (2003) find the highest temperature, with 5925K. The 2 colour indexes $B-V = 0.606$ and $b-y = 0.391$ confirm a higher temperature than the Sun. Despite the large dispersion in Teff, the dispersion in [Fe/H] is low, with an average exactly solar. HD095128 is more luminous than the Sun. Allende Prieto et al (1999) quote a mass of $0.96 M_{\odot}$ and an astrometric gravity of logg=4.23, in good agreement with the averaged spectroscopic gravity of logg=4.28 quoted in Table 4. It shows that HD095128 has already evolved from the main sequence.

3.7. HD042618

The only mention of HD042618 is by Fesenko (1994) in his solar type star study. The 2 available estimates of its temperature differ by 120K, but $B-V = 0.632$ suggests that the hottest one, 5775K, is the most likely. The cold temperature scale adopted by Reddy et al (2002) implies a low metallicity of [Fe/H]=-0.16, which might be closer to the solar one in fact. It is not very clear however, because its absolute magnitude $M_{\rm V} = 5.05$ combined with a solar temperature would not be compatible with being on the solar composition ZAMS.

3.8. HD071148

Like HD042618, HD071148 was recorded by Fesenko (1994) but did not receive much attention as a solar analog. Its effective temperature is subject to a controversy between partisans of a low temperature scale (Reddy et al 2002 and Chen et al 2003) giving a temperature of about 5710K and Mishenina et al (2003) giving a temperature 140K higher. Again we find that the colour indexes indicate that this star is probably slightly hotter than the Sun. The 3 authors agree on the fact that its metallicity is nearly solar.

Interestingly, the radial velocity of HD071148 has been monitored during several years by Naef et al (2003) who found that it is constant within 10 $\mathrm{m\,s^{-1}}$, ruling out the presence of a low mass companion.

3.9. HD186427

HD186427 (16 Cyg B) is one of the best solar twin candidates of the Lowell Fall Workshop and also a planet-host star. Its UV spectrum was qualified as "indistinguishable from solar" by Hardorp (1978), a similarity confirmed by Fernley et al (1996). There is a remarkable agreement between the 10 authors who have estimated its temperature, colder than the Sun by only ∼20K. Only Laws & Gonzalez (2001) and Gonzalez (1998) used a significantly lower temperature scale. HD186427 differs from the Sun mainly by its higher metal content, and by a higher luminosity.

3.10. HD010145

HD010145 has never been mentioned as a solar analog and was little studied before. The recent spectroscopic analysis performed by Mishenina et al (2003) shows that it is colder than the Sun by 100K, but with a similar gravity and metal content. It is the coldest of our Top Ten together with HD089269, the latter one having bluer colour index consistent with its lower metallicity. HD010145 has a lower luminosity than the Sun, indicating either a lower age or a lower mass.

4. Li content, activity, ages

In this section we compare qualitatively the Li content of our Top Ten solar analogs with that of the Sun. The solar photosphere is known to be highly depleted in Li, as is the case for many solar type stars. This depletion is however subject to various interpretations, involving rotation, convection, or the presence of a planetary system. The correlation of age with Li depletion has also been often discussed but not fully established.

The ^{7}Li doublet resonance lines at 670.78 nm and 670.79 nm are well placed in the middle of the 66th order of the ELODIE spectra. In Fig. 3, for each of our Top Ten, the Li region was superposed on the solar spectrum, showing that 6 of them are depleted in Li like the Sun whereas the 4 others show a pronounced Li feature. The most pronounced feature concerns HD071148 and HD010307. A weaker feature is also present in the spectra of HD095128 and HD146233.

More clearly than the Li content, the chromospheric activity of a solar type star is directly connected to its age. Thus it would have been extremely interesting to look at the chromospheric activity revealed by the central depth of the Ca II H and K lines, and of the Ca II triplet lines at 852 nm. Unfortunatly the NIR Ca II triplet is not in

the spectral range of ELODIE and the H and K lines appear on the border of the 2nd and 3rd orders which are underilluminated. The core of the H_α line is also an indicator of chromospheric activity, but we were not able to detect any significant difference of depth, even for the 4 stars having a higher Li content. According to Soderblom (1985), HD071148, HD010307 and HD095128 show CaII emission strengths and rotation similar to the Sun, suggesting a weak activity. Hall & Lockwood (2000) found an activity cycle in HD146233 with an amplitude slightly greater than that of the Sun. Thus these 4 stars presenting a pronounced Li feature do not seem to be enormously more active than the Sun. Two other analogs are part of Soderblom's study, HD010145 and HD168009; they do not exhibit evidence of a higher activity than the Sun.

Several of our Top Ten had their age estimated by Ibukiyama & Arimoto (2002) : 7.02 Gyr for HD168009, 7.32 Gyr for HD010307, 6.92 Gyr for HD095128, 6.65 Gyr for HD071148. According to Cayrel de Strobel & Friel (1998), HD146233 has an age of 6 Gyr. Thus one can find stars older than the Sun which have a higher Li content.

5. Solar analogs selected by other methods

The ELODIE library includes the spectra of several stars which were considered in previous studies as high rank solar analogs. We will focus here on HD217014 (51 Peg), HD028099 (Hy VB 64) and HD186408 (16 Cyg A).

With our purely differential method HD186408 is within the 20 best solar analogs among our list of 208 dwarfs. A dozen recent determinations of its atmospheric parameters are available and give on average Teff=5780K, logg=4.26, [Fe/H]=+0.07. Its visual absolute magnitude is $M_{\rm V} = 4.29$, to be compared to $M_{\rm V} = 4.56$ for its companion HD186427 and $M_{\rm V\odot} = 4.82$ showing that HD186408 is more massive and evolved.

HD217014 and HD028099 obtained a lower score in the TGMET output despite their similar effective temperature and gravity to the Sun. These 2 stars have also been very much studied, especially HD217014 because of its planet. The latest determination of its atmospheric parameters led to Teff=5805K, logg=4.51, [Fe/H]=+0.21 (Santos et al 2003). Thus stronger metallic lines explain that it is not a good spectroscopic analog of the Sun. HD028099 was found to have Teff=5800K, logg=4.40, [Fe/H]=+0.10 by Paulson et al (2003). This star is not considerably more metal rich than the Sun, but it is known to be younger and to have a high chromospheric activity. Looking closely at its spectrum shows that its lines are not as deep as those in the solar spectrum.

We have also searched for photometric solar analogs in the ELODIE library by selecting stars having the same colours and absolute magnitude as the Sun. Four stars fall in the narrow range $4.6 < M_{\rm V} < 5.0, 0.63 < B-V < 0.68, 0.16 < U-B < 0.23, 0.40 < b-y < 0.42$: HD001835 (BE Cet), HD076151, HD146233, HD159222. HD076151 in not in our Top Ten but it is at the 14th position. It is a well studied star, with recent determinations of its atmospheric parameters in good agreement, giving on average Teff=5774K, logg=4.39, [Fe/H]=+0.06. It was also one of the good solar twin candidates discussed by Cayrel de Strobel (1996). However, this star is younger than the Sun (3.04 Gyr estimated by Ibukiyama & Arimoto 2002), with a stronger activity and faster rotation (Pizzolato et al 2003) and presents a pronounced Li feature. In combination with a higher metal abundance, this may explain why it was not at higher rank in the TGMET output. HD001835 is a variable star of the BY Dra type which renders its photometry suspect. It was also discussed by Cayrel de Strobel (1996) as a good solar analog for the temperature and gravity but not for Li, chromospheric activity and age. Its young age is assessed by its membership of the Hyades moving group and its high activity is confirmed by Pizzolato et al (2003). It is also more metal-rich than the Sun ([Fe/H]=+0.13 estimated by Mishenina et al 2003) and its distance to the solar spectra computed by TGMET is very large. Its activity is clearly seen in its

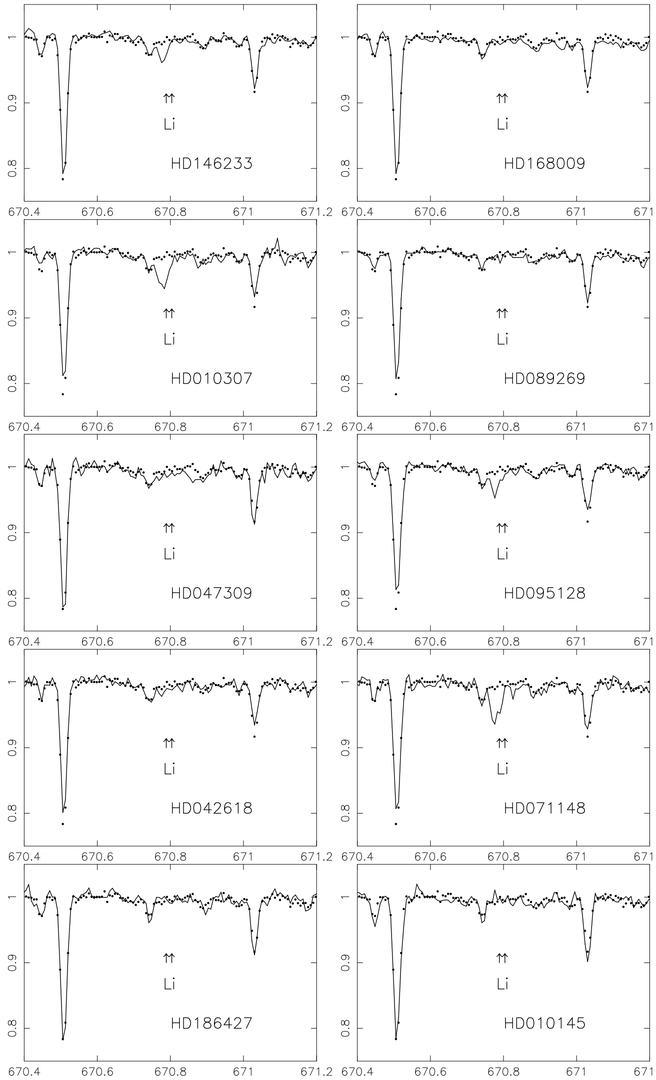

Fig. 3. Comparison between the Li I 670.7 nm region of the Sun (spectrum 00903, dotted line) and of each Top Ten solar analog

H_α line, which is shallower than in the Sun. HD159222 the 11th star in the TGMET output. It is thus a good photometric and spectroscopic solar analog. Moreover its age is also very similar (4.56 Gyr estimated by Ibukiyama & Arimoto 2002). Several determinations of Teff are available for this star, showing an impressive dispersion : 5708 K by Blackwell & Lynas-Gray (1998), 5770 K by Alonso et al (1996a), 5834 K by Mishenina et al (2003), 5852 K by di Benedetto (1998).

We have also observed that many spectra were polluted by telluric lines in the red orders, and that order 39 including the MgI triplet was a powerful discriminator of solar resemblance. We have thus performed the TGMET comparison of the 8 solar spectra with the library using only this order. This has greatly modified the order of our list, HD146233 keeping however its highest rank. The five closest stars are part of the Top Ten list : HD146233, HD047309, HD168009, HD042618 and HD186427. The 4 stars of the Top Ten list with the lowest temperatures (HD010145 and HD089269) and the highest temperatures (HD010307 and HD095128) are pushed away. Five new stars appear in the 10 closest solar analogs : HD195034, HD159222 (also a good photometric analog), HD187123, HD186104, HD005294. The photometric analog HD076151 is at the 11th position.

The parameters of the solar analogs discussed in this section are listed in Table 3. All of them, except HD005294, are more metal-rich than the Sun.

6. Discussion

It is interesting to note that, despite the great similitude of the optical spectrum of our Top Ten solar analogs to that of the Sun, their atmospheric parameters can differ significantly. Effective temperatures span ±100K on both sides of the solar value, logg values span the interval [4.09 ; 4.58] and [Fe/H] span the interval [-0.23 ; +0.11]. Several interpretations can explain this dispersion. On the one hand, authors do not use the same temperature scale and model atmospheres. Temperature scales can differ by more than 150K as we have seen. It is very important that authors agree on temperatures because this parameter has a strong impact on abundance determinations. Uncertainties which affect the stellar parameter determinations have been discussed by Asplund (2003) to be of the order of 50K to 100K in Teff, 0.2 dex for logg and 0.1 dex for [Fe/H]. On the other hand, we cannot expect finding a perfect twin having all its parameters exactly solar, especially in an incomplete sample. Finally, temperature and metallicity have contrary effects on the overall spectrum which may compensate in some cases (ex HD089269 or HD187123). It is also possible that other effects act on the spectra. Observing conditions and telluric lines are the most obvious, but intrinsic stellar properties also have an influence on the spectrum. We have mentioned chromospheric activity and rotation, but the abundance of other elements than iron, turbulent motions, spots on the stellar surface may be different than in the Sun. For instance, when using TGMET only in the MgI triplet region, the Mg abundance of the star may have a strong weight.

Colour indexes of the Top Ten solar analogs also span intervals as large as 0.073 in $B-V$, 0.032 in $b-y$, 0.099 in $U-B$, and absolute magnitudes range from $M_{\rm v} = 4.31$ to $M_{\rm v} = 5.06$. Fig. 4 represents their distribution in Teff vs colour and HR diagrams together with the other analogs discussed in Sect. 5 and the rest of the ELODIE library, restricted to $-0.25 <$ [Fe/H] $< +0.15$. The Strömgren index $b-y$ is clearly the one which presents the lowest dispersion in its relation with Teff. Like atmospheric parameters, magnitudes and colours are affected by uncertainties and a lack of homogeneity. Absolute magnitudes are computed from excellent parallaxes but averages of old and inhomogeneous apparent magnitudes. Tycho2 (Høg et al 2000) is a recent photometric catalogue of good quality but its B and V passbands do not correspond to the Johnson standard system and transformations, also affected by calibration uncertainties, have to be used. A small fraction of the dispersion may also be due to interstellar absorption, even if our targets are closer than 50 pc. But we interpret the larger part of the dispersion to mean that our incomplete sample of 208 G dwarfs includes stars of various ages and states of evolution resulting in a variety of astrophysical properties, because the ELODIE library was built to represent the stellar content in the solar neighbourhood, not solar analogs.

We have seen in previous sections that good photometric analogs are not always good spectroscopic analogs. HD001835 is a good example of a star having similar colours and absolute magnitude as the Sun but which is considerably different in respect to its age, activity and metal content. Thus photometry is not able to discriminate between these effects whereas high resolution spectroscopy can. In contrast the direct comparison of high resolution spectra used alone classify as solar analogs stars having a large range of atmospheric parameters. We conclude that a good strategy to find other solar twins than HD146233, and perhaps better ones, would be to select photometric analogs in large catalogues, then select with Hipparcos those that have a similar absolute magnitude to the Sun, then submit their high resolution spectrum to the TGMET comparison. We have scanned the GCPD, Strömgren and Hipparcos catalogues with the drastic criterion used in Sect. 5 to identify photometric analogs and found only 27 candidates, 4 being already in the ELODIE library, 15 others observable with ELODIE. We plan to observe them soon in order to complete this work.

7. Conclusion

We have presented the 10 stars of the ELODIE library which exhibit the closest optical spectrum to the Sun at a resolution of 42000. They have colours, absolute magnitudes, atmospheric parameters and Li content which span a range of values larger than expected. It is surprising that a star like HD089269, colder, more metal poor and less luminous than the Sun is at the 4th position,

Table 3. Fondamental data for solar analogs mentioned in Sect 5. Only the most recent determination of atmospheric parameters is listed. The second colomn indicates how the star was selected as a solar analog (P : photometry, L : Lowell workshop, Mg : TGMET on the Mg I triplet region)

Star name	method	$B-V$	$b-y$	$U-B$	M_V	Teff	log g	[Fe/H]	source
HD186408	L	0.645	0.410	0.187	4.29	5803	4.20	+0.02	Mishenina et al (2003)
HD217014	L	0.665	0.416	0.224	4.53	5805	4.51	+0.21	Santos et al (2003)
HD028099	L	0.660	0.411		4.75	5800	4.40	+0.10	Paulson et al (2003)
HD076151	P	0.662	0.413	0.217	4.83	5776	4.40	+0.05	Mishenina et al (2003)
HD001835	P	0.659	0.409	0.226	4.84	5790	4.50	+0.13	Mishenina et al (2003)
HD005294	Mg	0.650	0.401	0.174	5.03	5779	4.10	-0.17	Mishenina et al (2003)
HD159222	P+Mg	0.637	0.406	0.172	4.67	5834	4.30	+0.06	Mishenina et al (2003)
HD186104	Mg	0.631	0.412		4.62	5753	4.20	+0.05	Mishenina et al (2003)
HD187123	Mg	0.619	0.405		4.43	5855	4.48	+0.14	Santos et al (2003)
HD195034	Mg	0.610	0.408		4.84				

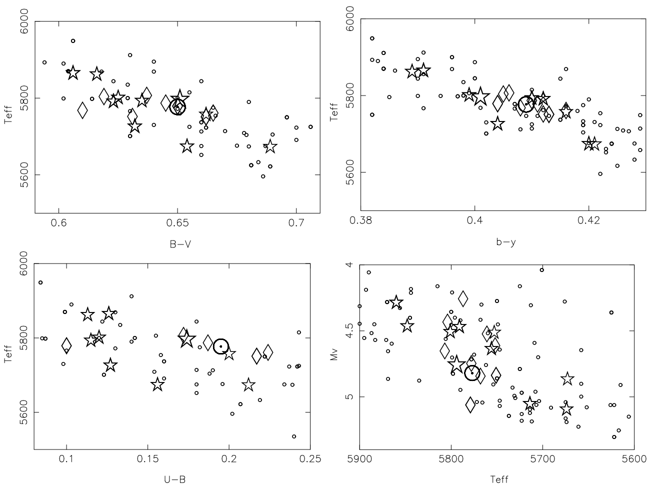

Fig. 4. Distribution of the ELODIE library (small dots), the Top Ten solar analogs (stars), other solar analogs (Sect. 5, diamonds) and the Sun in Teff vs colour and HR diagrams. The solar twin HD146233 is shown with a larger symbol.

whereas HD076151, having similar colours, absolute magnitude and atmospheric parameters is only at the 14th position. Activity may play an important role in discrimination. We have shown for instance that the good photometric analog HD001835 was a very bad spectroscopic analog because of its high activity. One also has to take into account, when comparing colours, absolute magnitudes and atmospheric parameters to those of the Sun, that these quantities are affected by significant uncertainties. Effective temperatures are particularly in question, with determinations for the same star differing by nearly 200K in some cases. Our method consisting in measuring distances between spectra is powerful but it is also affected by uncertainties due to observing conditions, especially the pollution by telluric lines, which may perturb the order of the classification.

Among our Top Ten, several stars have never been mentioned before as solar analogs and have been very little studied. They are good candidates for planet hunting, especially HD047309 which is slightly more metal rich than the Sun. Two of our solar analogs, HD095128 and HD186427, are already known to have planets. HD159222 and HD076151 are also good candidates because they are good spectroscopic analogs (in the Top 15) and good photometric analogs.

The conclusion of this work is that none of the methods to search for solar twins is satisfactory when used by itself. The methods that have been already used are the comparison of colour indexes, of absolute magnitudes, of UV spectral energy distributions, of atmospheric parameters and of high resolution optical spectra. All these methods are affected by uncertainties and none of them is able to describe sufficiently all the stellar properties. Combining them is the best way to minimize their drawbacks, uncertainties and insufficiencies. Finally HD146233 is the only star in the ELODIE library which merits the title of solar twin because it has passed the filter of all methods. It is not however a perfect twin and differs from the Sun by its higher Li content, slightly higher age (6 Gyr against 4.6 Gyr for the Sun) and higher luminosity ($M_V = 4.77$ against $M_{V\odot} = 4.82$).

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References

Adelman S.J., 2001, A&A 367, 297

Allende Prieto C., Garcia Lopez R.J., Lambert D.L., Gustafsson B., 1999, AJ 527, 879

Allen's Astrophysical Quantities 4^{th} edition, 2000, Arthur N. Cox Editor

Alonso, A., Arribas, S., & Martínez-Roger, C., 1999, A&A 139, 335

Alonso, A., Arribas, S., & Martínez-Roger, C., 1998, A&AS 131, 209

Alonso, A., Arribas, S., & Martínez-Roger, C., 1996a, A&AS 117, 227

Alonso, A., Arribas, S., & Martínez-Roger, C., 1996b, A&A 313,873

Asplund M., 2003, in Highlights of Astronomy, Vol 13, P.E. Nissen and M. Pettini eds.

Baranne, A., Queloz, D., Mayor, M., et al., 1996, A&A 119, 373

Blackwell, D.E. & Lynas-Gray, A.E, 1998, A&A 129, 505

Cayrel de Strobel, G., 1996, A&AR 7, 243

Cayrel de Strobel G. & Bentolila C., 1989, A&A 211, 324

Cayrel de Strobel G. & Friel E.D., 1998, in Solar Analogs, Proc. of the 2nd Lowell Fall Workshop, ed. J.C. Hall

Cayrel de Strobel, G., Knowles, N., Hernandez, G., Bentolila, C., 1981, A&A 94, 1

Chen, Y.Q., Nissen, P.E., Zhao, G., Zhang, H.W., Benoni, T., 2000, A&A 141, 491

Chen, Y.Q., Zhao, G., Nissen, P.E., Bai G.S., Qiu H.M., 2003, ApJ 591, 925

Deliyannis, C.P., Cunha, K., King, J.R., Boesgaard, A.M., 2000, AJ 119, 2437

di Benedetto, G.P, 1998, A&A 339, 858

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E., Tomkin, J., 1993, A&A 275, 101

Feltzing, S., Gustafsson, B., 1998, A&A 129, 237

Fernley, J.; Neckel, H.; Solano, E.; Wamsteker, W., 1996, A&A 311, 245

Fesenko B.I., 1994, AZh 71, 297

Friel, E., Cayrel de Strobel, G., Chmielewski, Y., Spite, M., Lebre, A., Bentolila, C., 1993, A&A 274, 825

Fuhrmann, K., Pfeiffer, M.J., Bernkopf, J., 1997, A&A 326, 1081

Fuhrmann, K., Pfeiffer, M.J., Bernkopf, J., 1998, A&A 336, 942

Gonzalez, G., 1998, A&A 334, 221

Gratton, R.G., Carretta, E., Castelli, F., 1996, A&A 314, 191

Gray D.F., 1995, PASP 107, 120.

Hall, J.C., Lockwood G.W., 2000, ApJ 43, L45

Hardorp, J., 1978, A&A 63, 383

Harmanec P., 1998, A&A 335, 173

Hauck, B.; Mermilliod, M., 1998, A&AS 129, 431

Henry T.J., McCarthy D.W.Jr, Freeman J., Christou J.C., 1992, AJ 103, 1369

Høg E., Fabricius C., Makarov V.V., Urban S., Corbin T., Wycoff G., Bastian U., Schwekendiek P., Wicenec A., 2000, A&A 355, 27

Ibukiyama A., Arimoto N., 2002, A&A 394, 927

Katz, D., Soubiran, C., Cayrel, R., Adda, M., Cautain, R., 1998, A&A 338, 151

Kidger M.R., Martín-Luis F., 2003, AJ 125, 3311.

Kotvtyukh V.V., Soubiran C., Belik S.I., Gorlova N.I., 2003, A&A 411, 559

Kukarkin, B. V.; Kholopov, P. N.; Artiukhina, N. M.; Fedorovich, V. P.; Frolov, M. S.; Goranskij, V. P.; Gorynya, N. A.; Karitskaya, E. A.; Kireeva, N. N.; Kukarkina, N. P.; Kurochkin, N. E.; Medvedeva, G. I.; Perova, N. B.; Ponomareva, G. A.; Samus, N. N.; Shugarov, S. Y., 1981, Nachrichtenblatt der Vereinigung der Sternfreunde e.V. (CDS : II/140)

Laws, C., Gonzalez, G., Walker, Kyle M., Tyagi, S., Dodsworth, J., Snider, K., Suntzeff, N.B., 2003, AJ, 125, 2664

Laws, C., Gonzalez, G., 2001, A&A 553, 405

Martin, C.; Mignard, F.; Hartkopf, W. I.; McAlister, H. A., 1998, A&AS 133, 149

Mashonkina L., Gehren T., 2001, A&A 376, 232

Mermilliod, J.-C.; Mermilliod, M.; Hauck, B., 1997, A&AS 124, 349

Mishenina T.V., Soubiran C., Kovtyukh V.V., Korotin S.A., 2003, A&A submitted

Naef D., Mayor M., Korzennik S.G., Queloz D., Udry S., Nisenson P., Noyes R.W., Brown T.M., Beuzit J.L., Perrier C., Sivan J.P., 2003, A&A 410, 1051

Neckel H., 1986, A&A 169, 194

Paulson D.B., Sneden C., Cochran W.D., 2003, AJ 125, 3185

Pizzolato N., Maggio A., Micela G., Sciortino S., Ventura P., 2003, A&A 397, 147

Porto de Mello G.F., da Silva L., 1997, ApJ 482, L89

Prugniel, Ph.; Soubiran, C., 2001, A&A 369, 1048

Reddy B.E., Tomkin J., Lambert D.L., Prieto C.A., 2002, MNRAS 340, 304.

Santos, N.C., Israelian, G., Mayor, M., Rebolo, R., Udry, S., 2003, A&A 398, 363

Soderblom D.R., 1985, AJ 90, 2103

Soubiran, C., Katz, D., Cayrel, R., 1998, A&A 133, 221

Zhao, G., Gehren, T., 2000, A&A 362, 1077

Zhao, G., Chen, Y.Q., Qiu, H.M., Li, Z.W., 2002, A&A 124, 2224

Table 4. Fondamental data for our Top Ten solar analogs. Our adopted atmospheric parameters in bold characters are the mean values from the literature. The second column is the averaged TGMET distance of the corresponding star to the 8 solar spectra.

Star name	TGMET score	$B-V$	b-y	U-B	distance in pc	Absolute magnitude	Teff	log g	[Fe/H]	source (Teff, logg, [Fe/H])
Sun		0.64-0.66	0.40-0.41	0.17-0.20	0	4.80-4.84	5777	4.44	0.00	-
HD146233	2.019	0.651	0.401	0.174	14.0	4.77	5799	4.40	+0.01	Mishenina et al (2003)
							5789	4.49	+0.05	Porto de Mello & da Silva (1997)
							5794	**4.44**	**+0.03**	
HD168009	2.195	0.635	0.410	0.115	22.7	4.52	5826	4.10	-0.01	Mishenina et al (2003)
							5719	4.08	-0.07	Chen et al (2000)
							5826	-	-	di Benedetto (1998)
							5833	-	-	Blackwell & Lynas-Gray (1998)
							5781	-	-	Alonso et al (1996a)
							5801	**4.09**	**-0.04**	
HD010307	2.516	0.616	0.389	0.113	12.6	4.45	5881	4.30	+0.02	Mishenina et al (2003)
							5776	4.13	-0.05	Chen et al (2000)
							5825	4.33	-0.04	Gratton et al (1996)
							5874	-	-	Alonso et al (1996a)
							5898	4.31	-0.02	Edvardsson et al (1993)
							5848	**4.26**	**-0.02**	
HD089269	2.602	0.654	0.420	0.156	20.6	5.06	5674	4.40	-0.23	Mishenina et al (2003)
							5674	**4.40**	**-0.23**	
HD047309	2.628	0.623	0.412	-	42.4	4.47	5791	-	-	Kovtyukh et al (2003)
							5791	4.40	+0.11	Mishenina priv. com.
							5791	**4.40**	**+0.11**	
HD095128	2.758	0.606	0.391	0.126	14.1	4.31	5887	4.30	+0.01	Mishenina et al (2003)
							5861	4.29	+0.05	Laws et al (2003)
							5925	4.45	+0.05	Santos et al (2003)
							5788	4.31	+0.03	Zhao et al (2002)
							5731	4.16	-0.12	Chen et al (2000)
							5892	4.27	0.00	Zhao & Gehren (2000)
							5892	4.27	0.00	Fuhrmann et al (1998)
							5800	4.25	+0.01	Gonzalez (1998)
							5892	4.27	0.00	Fuhrmann et al (1997)
							5811	4.09	0.00	Gratton et al (1996)
							5882	4.34	+0.01	Edvardsson et al (1993)
							5860	**4.28**	**0.00**	

Star name	TGMET score	$B-V$	b-y	U-B	distance in pc	Absolute magnitude	Teff	log g	[Fe/H]	source (Teff, logg, [Fe/H])
Sun		0.64-0.66	0.40-0.41	0.17-0.20	0	4.80-4.84	5777	4.44	0.00	-
HD042618	2.857	0.632	0.404	0.127	23.1	5.05	5775	-	-	Kovtyukh et al (2003)
							5653	4.58	-0.16	Reddy et al (2002)
							5714	**4.58**	**−0.16**	
HD071148	2.907	0.625	0.399	0.120	21.8	4.65	5850	4.25	0.00	Mishenina et al (2003)
							5716	4.34	+0.03	Chen et al (2003)
							5703	4.46	-0.08	Reddy et al (2002)
							5756	**4.35**	**-0.02**	
HD186427	2.934	0.662	0.416	0.200	21.4	4.56	5752	4.20	+0.02	Mishenina et al (2003)
							5765	4.46	+0.09	Santos et al (2003)
							5685	4.26	+0.07	Laws & Gonzalez (2001)
							5760	4.40	+0.06	Deliyannis et al (2000)
							5700	4.35	+0.06	Gonzalez (1998)
							5773	4.42	+0.06	Feltzing & Gustafsson (1998)
							5766	4.29	+0.05	Fuhrmann et al (1997)
							5752	-	-	di Benedetto, (1998)
							5767	-	-	Alonso et al (1996a)
							5753	4.33	+0.06	Friel et al (1993)
							5753	**4.35**	**+0.06**	
HD010145	3.003	0.689	0.421	0.212	36.7	4.87	5673	4.40	-0.01	Mishenina et al (2003)
							5673	**4.40**	**-0.01**	